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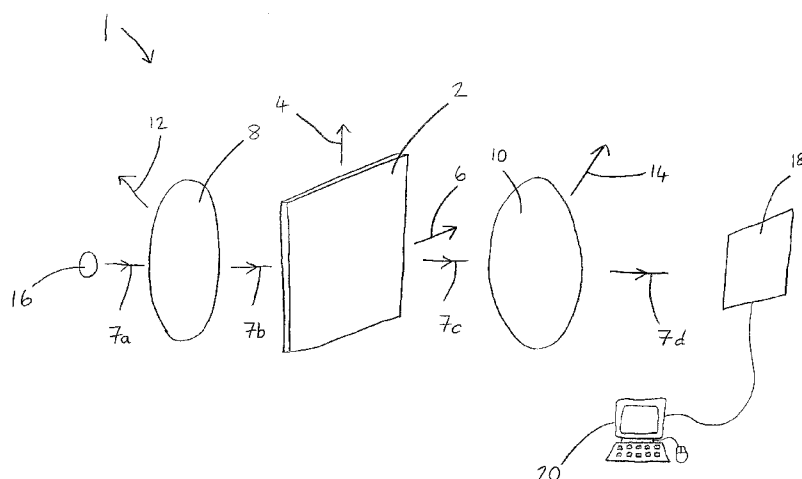


Fig. 1

(57) Abstract: A method of measuring a physical parameter, preferably temperature, around a nominal value of the physical parameter comprises providing a sensing material (2) in the vicinity of the physical parameter to be measured. The sensing material (2) has zero or near zero birefringence at the nominal value of the physical parameter. The method further comprises directing light (16) through the sensing material (2), measuring the retardance of the light (16) that has passed through the sensing material (2), and determining the value of the physical parameter from the retardance of the light (16) passing through the sensing material (2).

SENSING PHYSICAL PARAMETERS USING BIREFRINGENCE

5 This invention relates to measuring a physical parameter, e.g. temperature, using birefringent crystals.

10 There are many different types of apparatus used for measuring physical parameters. For example, pyroelectric and piezoelectric sensors are widely used for thermal and pressure sensing respectively. Pyroelectric sensors can also be used for thermal imaging. In these examples a material, typically a crystal, is used as a temperature or pressure sensor which is placed in the environment in which temperature or pressure is to be measured. Changes in pressure/temperature result in a voltage being generated within the crystal which can be detected, and the temperature or pressure can then be determined from the measured voltage.

15 Such sensors require the crystal to be intimately combined with the rest of the apparatus as wires need to be connected to the crystal to detect the voltage changes in it. The need to have measurement and control circuitry locally restricts where such sensors can be used, and also the intimate presence of other components of the apparatus to the crystal may create unknown systematic errors

20 in the measurement of the temperature or pressure.

It is also known to use birefringent materials, e.g. birefringent crystals, for measuring physical parameters, e.g. temperature, by using an interrogating light beam to detect changes in the birefringence of the material which occur with

25 changes in the physical parameter being measured. Since the crystal can be interrogated remotely by the light beam, only the crystal needs to be provided in the environment in which the physical parameter is to be measured. All the other components, i.e. the light source and measurement/processing electronics can be provided remotely. This allows a greater freedom in where the sensor can be used

30 and also makes the design of the electronics and their housing more straightforward.

However the inventor has recognised that known birefringence sensors can be improved and thus when viewed from a first aspect the present invention provides a

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method of measuring a physical parameter around a nominal value of the physical parameter comprising:

- providing a sensing material in the vicinity of the physical parameter to be measured, wherein the sensing material has zero or near zero birefringence at the nominal value of the physical parameter;
- directing light through the material;
- measuring the retardance of the light that has passed through the material;
- and
- determining the value of the physical parameter from the retardance of the light passing through the material.

The invention also extends to an apparatus for measuring a physical parameter around a nominal value of the physical parameter comprising:

- a sensing material, wherein the material has zero or near zero birefringence at the nominal value of the physical parameter;
- a light source arranged to direct light through the material;
- measuring means for measuring the retardance of the light that has passed through the material; and
- processing means for determining the value of the physical parameter from the retardance of the light passing through the material.

It has been appreciated by the inventor that using a sensing material to measure the parameter around a value at which material has zero or near zero birefringence affords a number of advantages. Near zero birefringence is defined herein to mean that the value of the birefringence of the material, at the nominal value of the physical parameter, gives an interference between the phase shifted waves of the outcoming light from the material which is in the fifth order or below, preferably in the third order or below.

One advantage of operating close to zero birefringence is that small changes in retardance can be measured which allows sensitive measurements of the physical property. When light passes through a birefringent material, the birefringence causes the two different polarisations of the light to experience a different refractive index and therefore it introduces a phase shift between the two different polarisations. This phase shift can be measured as a retardance, given by

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$$\delta = \frac{2\pi\Delta n t}{\lambda}$$

where δ is the phase shift, Δn is the birefringence, t is the thickness of the material and λ is the wavelength of the incident light. The retardance is given by $R = \Delta n t$. Therefore, if the thickness of the material is known, the birefringence of the material
 5 can be determined. As the birefringence of the material depends on the physical parameter being measured, the physical parameter can therefore be calculated from the determined value of the birefringence.

There are a number of methods by which the retardance, R , can be measured. In
 10 one set of embodiments the method uses the fact that the intensity of light after it has passed through the material is given by

$$I = I_0 \sin^2 \frac{\delta}{2} \sin^2 2\varphi$$

where I , is the measured resultant intensity, I_0 , is the incident intensity and φ is the angle between one of the birefringent axes of the material and the reference point
 15 at which the intensity is being measured. Clearly the intensity is a maximum when $\varphi = 45^\circ$.

Although the formula set out above gives the theoretical position, in practice systematic errors reduce the accuracy with which the fringes can be measured.
 20 The inventor has appreciated that these errors are effectively multiplied at higher orders so that more accurate measurements are possible in the low orders.

At zero or near zero birefringence it is straightforward to determine the interference order in which the material is operating by changing the value of the physical
 25 parameter to the nominal value to bring the material to zero birefringence where it is isotropic, and counting the number of orders from zero to the required operating range. This allows absolute measurements of the parameter to be made. By contrast if the material is operating well away from zero, as in previous birefringent sensors, then only the measurement of relative changes of the physical parameter
 30 is possible, these being measured in the same way either by measuring intensity changes within one order or, more commonly, changes in the number of intensity orders.

Another advantage of operating at zero or near zero birefringence is that the measurements are less sensitive to changes in the thickness of the material. This is because changes in the thickness do not affect the value of the retardance, $R = \Delta n t$, by very much if the value of the birefringence, Δn , is small.

5

Also related to the insensitivity to the thickness of the material, if the material has a birefringence near zero, is that the angle of orientation of the material relative to the direction of the incoming light is less important. This is because as the value of the birefringence, Δn , approaches zero, the material becomes more optically isotropic and therefore any material orientation effects become less and less important.

10

As the thickness of the material and the angle of orientation of the material relative to the direction of the incoming light are not critical, this simplifies the manufacturing of the apparatus as there is not then a need for highly accurate fabrication of the sensing material, nor highly accurate orientation of the sensing material relative to the apparatus and subsequent calibration.

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In one particular set of embodiments the material has a thickness, in the direction through which the light passes, of less than 1 mm, preferably less than 0.5 mm. As explained above it may be desirable to have the material relatively thin as the absolute value of differences in thickness traversed with different angles of orientation is minimised.

20

Also if the material is thin, i.e. the value of t is small, as the intensity of the light after it has passed through the material is dependent on the retardance, $R = \Delta n t$, then changes in the birefringence, Δn , will produce only small changes in the retardance, R . If the retardance changes only by a small amount then the change in intensity can be kept within one order and hence accurate measurements of the change in the parameter being measured can be made. Conversely, if the material is thick, then even very small changes in the birefringence will result in large changes in the retardance, producing changes in the intensity which span a large, unknown, number of orders unless the material is very close to zero birefringence. It may be seen therefore that there may be a trade-off between thickness of the sensing material and proximity to zero birefringence at the nominal parameter value.; the closer the birefringence is to zero, the thicker the crystal is able to be, while still keeping the intensity changes within one order. In such cases the thickness is less

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critical although will still be constrained by material costs and .the optical absorption of the material.

5 In a preferred set of embodiments the apparatus comprises an analyser through which the light it passed after passing through the material, thereby polarising the outcoming light. The analyser preferably has an angle of polarisation of between 40° and 50° - e.g. 45° to one of the birefringent axes of the material. This enables the outcoming light to be viewed at its point of maximum intensity, with the intensity simply depending on the phase shift, δ from which the retardance and birefringence
10 can be determined.

To further simplify the measurement of the physical parameter, preferably the light source providing the incident light is polarised and therefore preferably the apparatus comprises a polariser to polarise the light source. In this preferred set of
15 embodiments the polariser is placed between the light source and the material such that polarised light is incident upon the material. Preferably the angle of polarisation of the polariser is between 40° and 50° - e.g. 45° to one of the birefringent axes of the material, and, in the embodiments in which an analyser is provided, preferably between 85° and 95° - e.g. 90° to the angle of polarisation of
20 the analyser. Therefore in a preferred set of embodiments the apparatus comprises an analyser and a polariser which are used together as "crossed polarisers" through which the light passes before the retardance is measured.

There are, however, other ways to measure the physical parameter. For example
25 in another set of embodiments the apparatus comprises a rotating polariser and a circular-polarising analyser, i.e. instead of the analyser and polariser in the previous set of embodiments. The provision of a rotating polariser and a circular-polarising analyser gives a greater sensitivity to the measurement of the physical parameter, through measurement of the intensity which in this set of embodiments is given by

$$30 \quad I = \frac{I_0}{2} [1 - 2 \sin(2\omega\tau - 2\phi) \sin \delta]$$

where τ is the time, ω is the frequency of rotation of the rotating polariser and the other terms are the same as previously.

The light source can comprise a white light source or a monochromatic light source. Using a white light source affords a benefit derived from the fact that white light comprises a plurality of different wavelengths which each experience a slightly different refractive index when they pass through the material. Therefore the different wavelength components of the white light are phase shifted by slightly different amounts when they pass through the material such that an interference pattern of the different phase shifted waves can be observed. For some wavelengths the phase shift results in constructive interference while for other wavelengths the phase shift results in destructive interference. Therefore the outcoming light from the material appears coloured. However, these colour changes become washed out at higher orders as the interference between phase shifted waves is smeared out and therefore accurate measurements can no longer be made.

Use of a monochromatic source with a (near) zero birefringent sensing material in accordance with the invention demonstrates the high sensitivity which embodiments of the invention can enable. It has been found that at (near) zero birefringence the light passing through the sensing material enables changes of 1 part in 10^7 to be detected.

A Michel-Lévy birefringence colour chart can be used to determine, from the colour of the outcoming light and the thickness of the material, the value of the birefringence of the material. This does not work for monochromatic light as the outcoming light from the material results in an interference pattern in which only the intensity varies, and therefore the order of the interference cannot be directly determined. However if it is known at which order the apparatus is operating, the changes in intensity can be used to determine the changes in birefringence.

Using the Michel-Lévy chart either small changes in intensity or colour within a single order can be measured to determine the change in birefringence and hence the change in the physical parameter, or the changes in intensity across a number of orders, i.e. by counting the number of interference fringes, can be measured.

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The light source could comprise any suitable light source, e.g. an incandescent lamp, a light emitting diode, a laser, a gas discharge lamp, depending on whether a white light or monochromatic light source is to be used.

- 5 The physical parameter to be measured could be any to which the birefringence of the sensing material is sensitive. Such physical parameters include pressure, stress, strain, electric field. In a particular set of embodiments the physical parameter to be measured is temperature. All of these physical parameters act on the material in a way which causes a stress between the molecules of the material, thereby changing its birefringence.

- 10 The material could comprise any birefringent material, such as plastic, e.g. cellophane or Polaroid, but in a preferred set of embodiments the material comprises a crystal. The crystal could comprise a liquid crystal, e.g. cholesteryl chloride or cholesteryl myristate, but preferably the crystal comprises a solid crystal. Examples of suitable solid crystals include lithium niobate (LiNbO_3) and lithium tantalate (LiTaO_3), though many other examples exist, e.g. barium titanate (BaTiO_3).

- 20 LiNbO_3 and LiTaO_3 are two crystals that are already widely accepted and used within the optics industry, e.g. they are used in pyroelectric detectors, and therefore can be obtained for a competitive price (about US\$220 for a 7.5cm diameter wafer that is 0.5mm thick and Y-cut to optical quality). Both of these crystals have a number of beneficial properties: they are very hard, highly stable, transparent, and have a low absorption of light, making them highly suitable for using in the apparatus of the present invention.

- 30 In a set of preferred embodiments the crystal is uniaxial. A uniaxial crystal is advantageous in some circumstances because the fact that it only has one axis along which birefringence can be measured simplifies the measurement. Since there is only a single birefringence value to measure the physical parameter being measured can be directly related to it. Also the value of the birefringence, Δn , may become zero at a known temperature, as in $\text{LiNbO}_3/\text{LiTaO}_3$, when the crystal becomes fully isotropic, i.e. isotropic when viewed along any direction through the crystal. In contrast, a biaxial crystal has three distinct optical axes, along which

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light experiences different refractive indices. Therefore a biaxial crystal is much harder to use to measure a physical parameter, as changes in the physical parameter being measured could result in all three of these refractive indices changing value. In particular the measurements would be sensitive to the precise orientation of the crystal to the interrogating beam.

In the embodiments in which LiNbO_3 and/or LiTaO_3 crystals are used, the crystal could comprise a congruent crystal or a stoichiometric crystal, or indeed a non-stoichiometric or non-congruent crystal. Normal crystal growth to produce LiNbO_3 and LiTaO_3 crystals often results in congruent crystals which are slightly deficient in lithium oxide (compared to the stoichiometric crystal of the same type). Advantageously the stoichiometry or congruency of the crystal can be varied to alter the nominal value of the physical parameter at which the birefringence of the crystal becomes zero. For example, when congruent LiNbO_3 is used to measure temperature, the temperature at which it has zero birefringence is about 900°C whereas when congruent LiTaO_3 or stoichiometric LiTaO_3 is used to measure temperature, the temperature at which it has zero birefringence is about -150°C or 100°C , respectively. There are a number of different techniques that can be used to change the stoichiometry and/or congruency of the crystal. Also possible is that the crystal comprises a mixture of two different crystals, e.g. lithium niobate (LiNbO_3) and lithium tantalate (LiTaO_3). In this way, the advantageous features of both of these crystals can be combined and the value of the physical parameter at which the crystal has zero birefringence can be varied.

In one preferred set of embodiments in which the physical parameter to be measured is temperature, a crystal comprising a mixture of different crystal compounds, e.g. LiNbO_3 and LiTaO_3 , is provided, with the proportions of each compound being varied to vary the temperature dependence of the birefringence, and therefore the nominal temperature at which the birefringence of the overall crystal becomes zero.

Additionally or alternatively the zero-birefringence of an individual crystal can be changed by altering the crystal in various ways. First the crystal can be doped with impurities, e.g. metal ions, which change the zero birefringence temperature. Second the congruency or stoichiometry of the crystal can be changed to vary the

zero-birefringence temperature. Such crystals could be used alone or in a mixture as described above in order to give the desired nominal temperature.

One method of varying the congruency or stoichiometry of a crystal is vapour transport equilibration (VTE). A description of the method of VTE can, for example, be found in Bordui et al. J. Appl. Phys., Vol. 71, No. 2, 15 January 1992 (for LiNbO_3), and Tian et al. Applied Physics Letters, Volume 85, No. 19, 8 November 2004 (for LiTaO_3). VTE can be used to transform a congruent crystal into a stoichiometric crystal, or indeed to any region in between. Using this and the methods described previously, the zero birefringence temperature can be varied over hundreds of degrees Celsius for a crystal. For example, by using a mixture of LiNbO_3 and LiTaO_3 , the zero birefringence temperature can be varied to lie at any temperature between about -100°C and 900°C , e.g. around room temperature. Alternatively, by using VTE, the zero birefringence temperature of LiTaO_3 can be varied to lie at any temperature between about -150°C and 100°C , again, for example, around room temperature. This clearly allows a wide range of embodiments of the invention for use at very different nominal temperatures.

In a preferred set of embodiments the thickness of the material varies across its area (the surface area through which the light source is directed, the area being perpendicular to the thickness). Having a material whose thickness varies is particularly beneficial for a (near) zero birefringence material as it helps to determine whether the measured changes in birefringence indicate an increase or decrease in the physical parameter to be measured. Thus for a given order of birefringence, it can be determined whether the measurement is on the up-slope or down-slope of the intensity signal by taking two or more retardance measurements corresponding to the light passing through different points of the material. As the thickness is different for these different retardance measurements, the value measured for the retardance will be different for each thickness. This enables the position on the intensity curves to be deduced, as the intensity varies with a different period at different thicknesses. Another method to deduce the position on the intensity curve is to use knowledge of the trend direction of the physical parameter being measured. In other words, when the parameter is known either to be increasing or decreasing the trend in the corresponding intensity response is measured. For example, if the temperature of a room is being measured, and it is

known that the temperature decreases at night and increases during the day, the position on the intensity curve can easily be deduced.

To use the variation in thickness of the material in this way requires the
5 birefringence of the material to be near zero, but not exactly zero, and therefore for this set of embodiments it is preferred for the material to comprise a material with a birefringence in the first few, e.g. second or third, orders. However, the birefringence still needs to be near zero, as if the material has a high birefringence, even small changes in its thickness will have a large effect on the change in the
10 retardance, and therefore the intensity signal will change across several orders of unknown number, making the measurement useless. When a material with near zero birefringence is used, the changes in intensity across the different thicknesses of material only cause a slight change in retardance which keeps the change in intensity within a single period and therefore enables the position on the intensity
15 curve to be determined.

The thickness of the material could be continuously varied across its surface area, e.g. by creating a wedge shaped material, or the thickness of the material could vary discretely across its surface area, e.g. in one or more steps. Taking the
20 example of a solid birefringent crystal, the crystal can be polished into different thicknesses across its surface area to provide the necessary variations in thickness.

As well as helping to determine which side of the slope on the intensity curve the measurement is, making two or more measurements of the intensity gives multiple
25 independent measurements thereby increasing the statistical accuracy of the measurement.

In a preferred set of embodiments the measuring means for measuring the retardance of the light that has passed through the material comprises means for
30 detecting the intensity of the light that has passed through the material. Therefore the associated method step of measuring the retardance of the light that has passed through the material preferably comprises measuring the intensity of the light that has passed through the material. The means for detecting the intensity of the light could comprise a photodetector, e.g. a photocell, photoresistor,
35 photodiode, CCD, or a photovoltaic cell.

In the set of embodiments in which a white light source is provided, preferably the colour of the light that has passed through the material is also measured.

Therefore preferably in this set of embodiments the apparatus comprises means for
5 measuring the wavelength of the light that has passed through the material, e.g. a spectrometer or spectrum analyser.

The method step of determining the value of the physical parameter from the measurement of the retardance of the light passing through the material could
10 comprise obtaining the value of the birefringence from a colour chart such as a Michel-Lévy birefringence colour chart as discussed previously, but in another set of embodiments the processing means is arranged to calculate the value of the physical parameter from the measurement of the intensity of the light, or from the measurement of the wavelength of the light that has passed through the material.

15 The method and apparatus of the present invention, as well as being applicable to measuring a single value of a physical parameter, can also be used in some embodiments to determine a spatial image of variations in the physical parameter, e.g. as in thermal imaging. A spatial image of the physical parameter can be
20 produced by dividing the material into a plurality of segments and directing light through each of the segments, thereby enabling a value of the physical parameter to be determined for each of the segments of the material. Each segment therefore corresponds to a pixel in the image. Ideally the material should be divided so that some or all of the segments of the material are mutually isolated as this enhances
25 their ability to produce independent measurements of the physical parameter. For example when measuring temperature to produce a thermal image, segmenting the material reduces thermal diffusion.

Where the apparatus is used to produce a spatial image of the physical parameter,
30 preferably the crystal comprises a reticulated solid crystal. Providing a reticulated crystal reduces the cross-talk within the crystal which therefore reduces the diffusion of the physical parameter, e.g. temperature, in the crystal and hence gives a more accurate measurement of the physical parameter. A reticulated crystal can be provided instead of, or in addition to, providing a segmented crystal.

In the set of embodiments in which the physical parameter being measured is temperature, i.e. a thermal image is being produced, preferably the apparatus comprises means for image the thermal scene onto the sensing material, e.g. an infra red lens. In order to make the light source remote from the thermal scene, i.e. not obscure it, preferably the apparatus comprises a half silvered mirror either to transmit the infra red radiation from the thermal scene and reflect the light to be directed through the material, or to reflect the infra red radiation from the thermal scene and transmit the light to be directed through the material.

Certain embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Fig. 1. shows a schematic of an embodiment of the invention for measuring temperature;

Fig. 2 shows a graph of the intensity signal of the light as a function of temperature after it has passed through a birefringent crystal;

Fig. 3 shows a birefringent crystal for use in accordance with the present invention; and

Fig. 4 shows a schematic of an embodiment of the invention for thermal imaging.

Fig. 1 shows a schematic of an embodiment of an apparatus 1 for measuring temperature in accordance with the present invention. The apparatus 1 comprises a birefringent crystal 2 which is placed in an environment in which the temperature is to be measured. This could for example be an industrial process in which precise control of the temperature is crucial but which might be a harsh environment not suited to having electronics. As can be seen, the crystal is the only component in the apparatus that needs to be provided in the environment in which the temperature is to be measured. No wires need to be attached to the crystal and all the other components can be located outside the environment so as to provide a remote sensor. Furthermore the birefringent crystal 2 is insensitive to external electromagnetic fields which therefore reduces systematic errors in the temperature measurement.

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In one specific example the birefringent crystal 2 is a Y-cut lithium tantalate (LiTaO₃) crystal which is 0.5 mm thick, has a width of 7.5 cm and has been treated by vapour transport equilibration (VTE) to arrange the temperature at which the crystal exhibits zero birefringence to be at room temperature (20°C). In accordance
 5 with the invention this would allow accurate measurement of temperatures near to room temperature e.g. between 10°C and 20°C with a sensitivity in the millidegree range. The temperature dependence of the birefringence of the birefringent crystal 2 is known and calibrated prior to use.

10 The axes 4, 6 of the different refractive indices of the crystal are arranged to be perpendicular to the axis 7a-d of the apparatus. The apparatus also comprises a polariser 8 and an analyser 10 whose respective polarisation axes 12, 14 are arranged to be perpendicular to each other and at 45° to the axes 4, 6 of the birefringent crystal 2, i.e. the polariser 8 and analyser 10 are used as crossed
 15 polarisers.

A white light source 16 is arranged to direct light along the axis 7a-d of the apparatus, first through the polariser 8, then through the birefringent crystal 2, then through the analyser 10 so that it is incident upon a spectrum analyser 18. The
 20 spectrum analyser 18 is connected to a computer 20 to read out and process the measurements from the spectrum analyser 18.

In operation of the apparatus 1, the birefringent crystal 2 is placed in an environment in which temperature is to be measured. The white light source 16 is
 25 arranged to direct light along the axis 7a through the polariser 8. The polariser 8 acts to polarise the light along its polarisation axis 12 so that the light now travelling along the axis 7b is polarised in a direction which is at 45° to the axes 4, 6 of birefringence of the birefringent crystal 2. The polarised light passes through the birefringent crystal 2 with the component of the light along each of the axes 4, 6 of
 30 birefringence experiencing a different refractive index which therefore introduces a phase shift, δ , between the two different polarisation light waves, which can be expressed as

$$\delta = \frac{2\pi\Delta n t}{\lambda}$$

The different wavelengths of light in the white light therefore experience slightly different refractive indices as they pass through the birefringent crystal 2 (as well as the different refractive indices along the two birefringent axes 4, 6 of the birefringent crystal 2). The phase-shifted light travels along the axis 7c from the birefringent crystal 2 and then passes through the analyser 10, which has its polarisation axis 14 perpendicular to the polarisation axis 12 of the polariser 8 and so at 45° to the axes 4, 6 of birefringence of the birefringent crystal 2. The polariser 8 therefore polarises the light again, which passes along the axis 7d and is incident upon the spectrum analyser 18. The dominant wavelength of the light at this point of the apparatus 1 can therefore be measured by the spectrum analyser, with the result of this wavelength measurement being sent to the computer 20.

The computer 20 is able to determine the value of the birefringence of the birefringent crystal 2, from the measurement of the dominant wavelength of the light using a calculation equivalent to reading off the value from a Michel-Lévy birefringence colour chart, based on a stored value for the thickness of the birefringent crystal 2. The wavelength of the light measured by the spectrum analyser 18 uniquely determines the retardance of the light and therefore the birefringence of the birefringent crystal 2. Once the birefringence of the birefringent crystal 2 is known, the temperature can easily be determined from knowledge of the calibrated relationship between the temperature and the birefringence of the birefringent crystal 2.

Alternatively a monochromatic light source, e.g. a laser, (positioned in exactly the same place as the white light source 16 shown in Fig. 1) can be used in conjunction with a detector, e.g. a photocell detector instead of the spectrum analyser 18 in Fig. 1, to measure the intensity of the light after it has passed through the birefringent crystal 2. Owing to the interference between the two phase shifted polarised waves of the monochromatic light, the changes in intensity can be measured by the photocell detector, in the same way that the changes of the dominant wavelength are measured by the spectrum analyser 18 in Fig. 1.

Fig. 2 shows a graph 21 of the changes in intensity, I , of the light with temperature, T , i.e. as the birefringence changes as a result of changes in temperature. At the zeroth order 22 the crystal has zero birefringence, this can be measured by

measuring isotropy, i.e. so there is no phase shift between the two different polarisations of the light travelling through the crystal 2. As has previously been explained, in some embodiments it is preferred to operate at the first order 24 or second order 26, i.e. near zero birefringence. In all of these cases, the temperature of the birefringent crystal 2 can be determined through measurement of the intensity of the light that has passed through the birefringent crystal 2 as has previously been described.

Fig. 3 shows an example of a birefringent crystal 2 for use in the apparatus of the present invention. The birefringent crystal 2 has been polished so that it has three different known thicknesses 28, 30, 32 in the direction of the axis 7a-d. This enables light to be directed through the birefringent crystal 2 so that it passes through all the three different thicknesses 28, 30, 32. Having a birefringent crystal 2 used in the apparatus in this way allows three different measurements of the retardance, $R = \Delta nt$, thereby enabling the position on the intensity curve to be determined as has been described previously and thus resolving the possible ambiguity of the intensity measurement owing to the multi-valued function of the intensity versus temperature.

Fig. 4 shows an embodiment in accordance with the present invention in which a segmented birefringent crystal 102 is used in the apparatus 1 shown in Fig. 1 instead of a single birefringent crystal 2. An infra red transparent lens 104 is used to produce an image of thermal scene from the infra red radiation 106 that it emits. The segmented birefringent crystal 102 is therefore representative of the temperature of the thermal scene, with any individual segment 108 of the segmented birefringent crystal 102 being associated with a small portion of the thermal scene.

Light 110 from a light source is directed through the segmented birefringent crystal 102 in the same manner as in Fig. 1, but in order to prevent the light source obscuring the thermal scene, a half-silvered mirror 112 is used to reflect the light 110 from the light source and transmit the infra red radiation 106 from the thermal scene. After the light 110 from the light source passes through the segmented birefringent crystal 102, it is detected by a detector as has been described previously in order for the temperature of the segmented birefringent crystal 102 to

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be determined. However in this embodiment, a separate temperature can be determined for each of the segments 108 in the segmented birefringent crystal 102. In this way a thermal image of the thermal scene can be produced with pixels corresponding to the segments 108. It will be appreciated that the different
5 segments 108 of the segmented birefringent crystal 102 in order to avoid thermal diffusion between the segments 108 which enables independent temperature measurements to be made.

It will be appreciated by those skilled in the art that many variations and
10 modifications to the embodiments described above may be made within the scope of the various aspects of the invention set out herein. For example a birefringent crystal strip, segmented in only one dimension, could be used instead of the segmented birefringent crystal 102 shown in Fig. 4, with the strip being scanned
15 across the image of the thermal scene to measure the temperature of each part of the thermal scene.

Claims

1. A method of measuring a physical parameter around a nominal value of the physical parameter comprising:
 - 5 providing a sensing material in the vicinity of the physical parameter to be measured, wherein the sensing material has zero or near zero birefringence at the nominal value of the physical parameter;
 - directing light through the sensing material;
 - measuring the retardance of the light that has passed through the sensing
 - 10 material; and
 - determining the value of the physical parameter from the retardance of the light passing through the sensing material.
2. A method as claimed in claim 1 wherein the birefringence of the sensing
- 15 material, at the nominal value of the physical parameter, gives an interference between the phase-shifted waves of the outcoming light from the sensing material which is in the fifth order or below, preferably in the third order or below.
3. A method as claimed in claim 1 or 2 wherein the sensing material has a
- 20 thickness, in the direction through which the light passes, of less than 1 mm, preferably less than 0.5 mm.
4. A method as claimed in claim 1, 2 or 3 comprising directing the light through a polarisation analyser after directing the light through the sensing material.
- 25 5. A method as claimed in claim 4 wherein the polarisation analyser has an angle of polarisation of between 40° and 50° , preferably 45° , to one of the birefringent axes of the sensing material.
- 30 6. A method as claimed in any preceding claim comprising directing polarised light through the sensing material.
7. A method as claimed in claim 6 comprising directing the light through a polariser prior to directing the light through the sensing material.

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8. A method as claimed in claim 7 wherein the polariser has an angle of polarisation of between 40° and 50° , preferably 45° , to one of the birefringent axes of the sensing material.
- 5 9. A method as claimed in any preceding claim wherein the physical parameter is temperature.
- 10 10. A method as claimed in any preceding claim wherein the sensing material comprises a crystal.
11. A method as claimed in claim 10 wherein the crystal comprises a solid crystal.
12. A method as claimed in claim 11 wherein the solid crystal comprises one or both of lithium niobate (LiNbO_3) and lithium tantalate (LiTaO_3).
- 15 13. A method as claimed in claim 10, 11 or 12 wherein the crystal is uniaxial.
14. A method as claimed in any preceding claims wherein the thickness of the sensing material varies across its area.
- 20 15. A method as claimed in claim 14 wherein the sensing material has a birefringence in the first, second or third orders.
- 25 16. A method as claimed in any preceding claim wherein the step of measuring the retardance of the light comprises measuring the intensity of the light that has passed through the sensing material.
- 30 17. A method as claimed in any preceding claim comprising directing white light through the sensing material.
18. A method as claimed in claim 17 comprising measuring the colour of the light that has passed through the sensing material.

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19. A method as claimed in claim 18 comprising measuring the wavelength of the light that has passed through the sensing material.
20. A method as claimed in any preceding claim comprising determining a
5 spatial image of the physical parameter.
21. A method as claimed in claim 20 wherein the sensing material is segmented.
- 10 22. A method as claimed in claim 20 or 21 wherein the sensing material comprises a reticulated crystal.
23. An apparatus for measuring a physical parameter around a nominal value of the physical parameter comprising:
15 a sensing material, wherein the sensing material has zero or near zero birefringence at the nominal value of the physical parameter;
a light source arranged to direct light through the sensing material;
measuring means for measuring the retardance of the light that has passed through the sensing material; and
20 processing means for determining the value of the physical parameter from the retardance of the light passing through the sensing material.
24. An apparatus as claimed in claim 23 wherein the birefringence of the sensing material, at the nominal value of the physical parameter, gives an
25 interference between the phase-shifted waves of the outcoming light from the sensing material which is in the fifth order or below, preferably in the third order or below.
25. An apparatus as claimed in claim 23 or 24 wherein the sensing material has
30 a thickness, in the direction through which the light passes, of less than 1 mm, preferably less than 0.5 mm.
26. An apparatus as claimed in claim 23, 24 or 25 comprising a polarisation
35 analyser through which the light is passed after passing through the sensing material.

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27. An apparatus as claimed in claim 26 wherein the polarisation analyser has an angle of polarisation of between 40° and 50° , preferably 45° , to one of the birefringent axes of the sensing material.
- 5
28. An apparatus as claimed in any of claims 23 to 27 comprising a polariser to polarise the light source.
29. An apparatus as claimed in claim 28 wherein the polariser is placed
10 between the light source and the sensing material such that polarised light is incident upon the sensing material.
30. An apparatus as claimed in claim 28 or 29 wherein the angle of polarisation of the polariser is between 40° and 50° , e.g. 45° , to one of the birefringent axes of
15 the sensing material.
31. An apparatus as claimed in claim 28, 29 or 30 comprising a polarisation analyser through which the light is passed after passing through the sensing material, wherein the angle of polarisation of the analyser is between 85° and 95° ,
20 e.g. 90° , to the angle of polarisation of the polariser.
32. An apparatus as claimed in any of claims 23 to 31 wherein the physical parameter is temperature.
- 25 33. An apparatus as claimed in any of claims 23 to 32 wherein the sensing material comprises a crystal.
34. An apparatus as claimed in claim 33 wherein the crystal comprises a solid crystal.
- 30 35. An apparatus as claimed in claim 34 the solid crystal comprises one or both of lithium niobate (LiNbO_3) and lithium tantalate (LiTaO_3),.
- 35 36. An apparatus as claimed in claim 33, 34 or 35 wherein the crystal is uniaxial.

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37. An apparatus as claimed in any of claims 23 to 36 wherein the thickness of the sensing material varies across its area.
- 5 38. An apparatus as claimed in claim 37 wherein the sensing material has a birefringence in the first, second or third orders.
39. An apparatus as claimed in any of claims 23 to 38 wherein the measuring means comprises means for detecting the intensity of the light that has passed
10 through the sensing material.
40. An apparatus as claimed in any of claims 23 to 39 wherein the light source comprises a white light source.
- 15 41. An apparatus as claimed in claim 40 comprising means to measure the colour of the light that has passed through the sensing material.
42. An apparatus as claimed in claim 41 comprising means to measure the wavelength of the light that has passed through the sensing material.
20
43. An apparatus as claimed in any of claims 23 to 42 comprising means to determine a spatial image of the physical parameter.
44. An apparatus as claimed in claim 43 wherein the sensing material is
25 segmented.
45. An apparatus as claimed in claim 43 or 44 wherein the sensing material comprises a reticulated crystal.

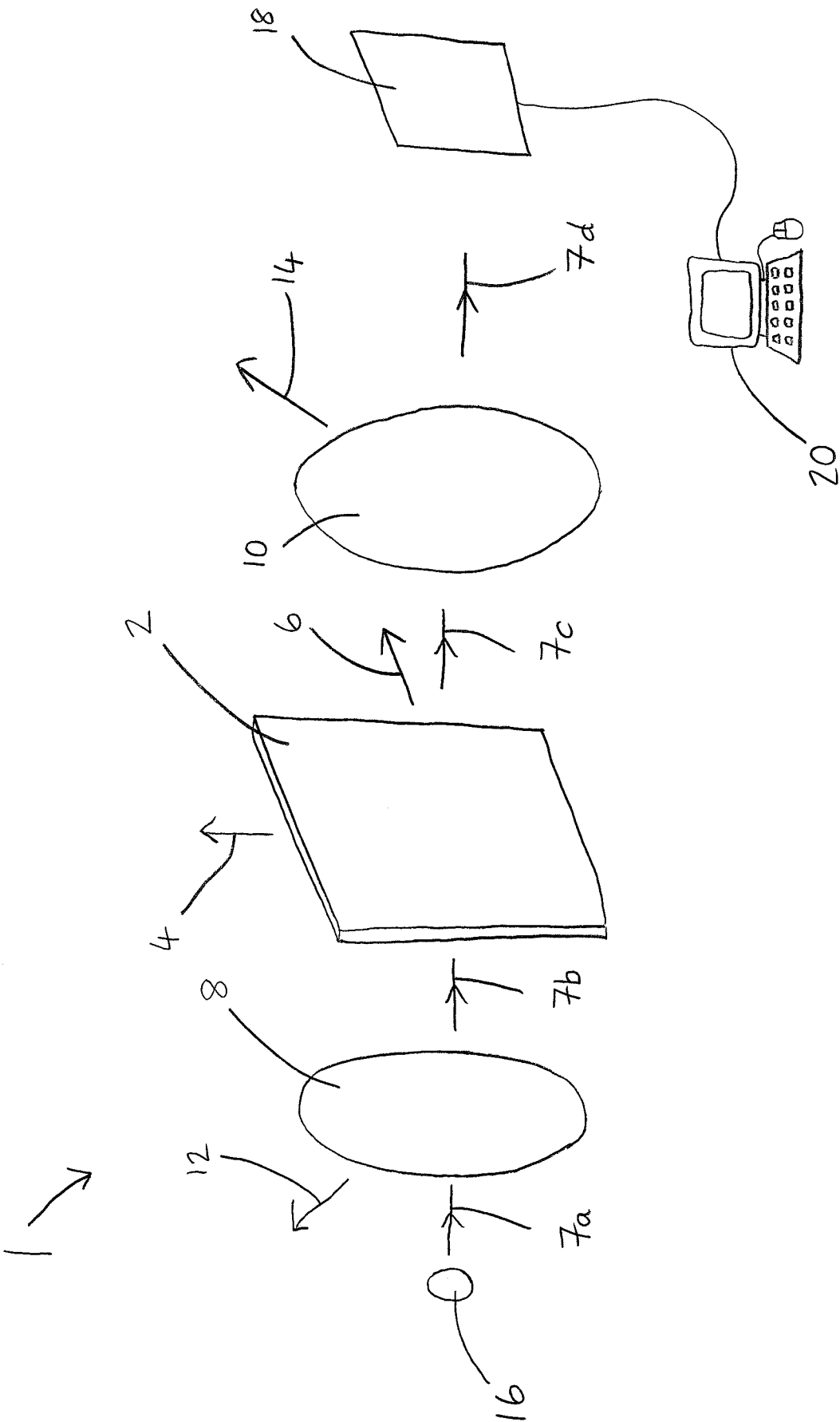


FIG. 1

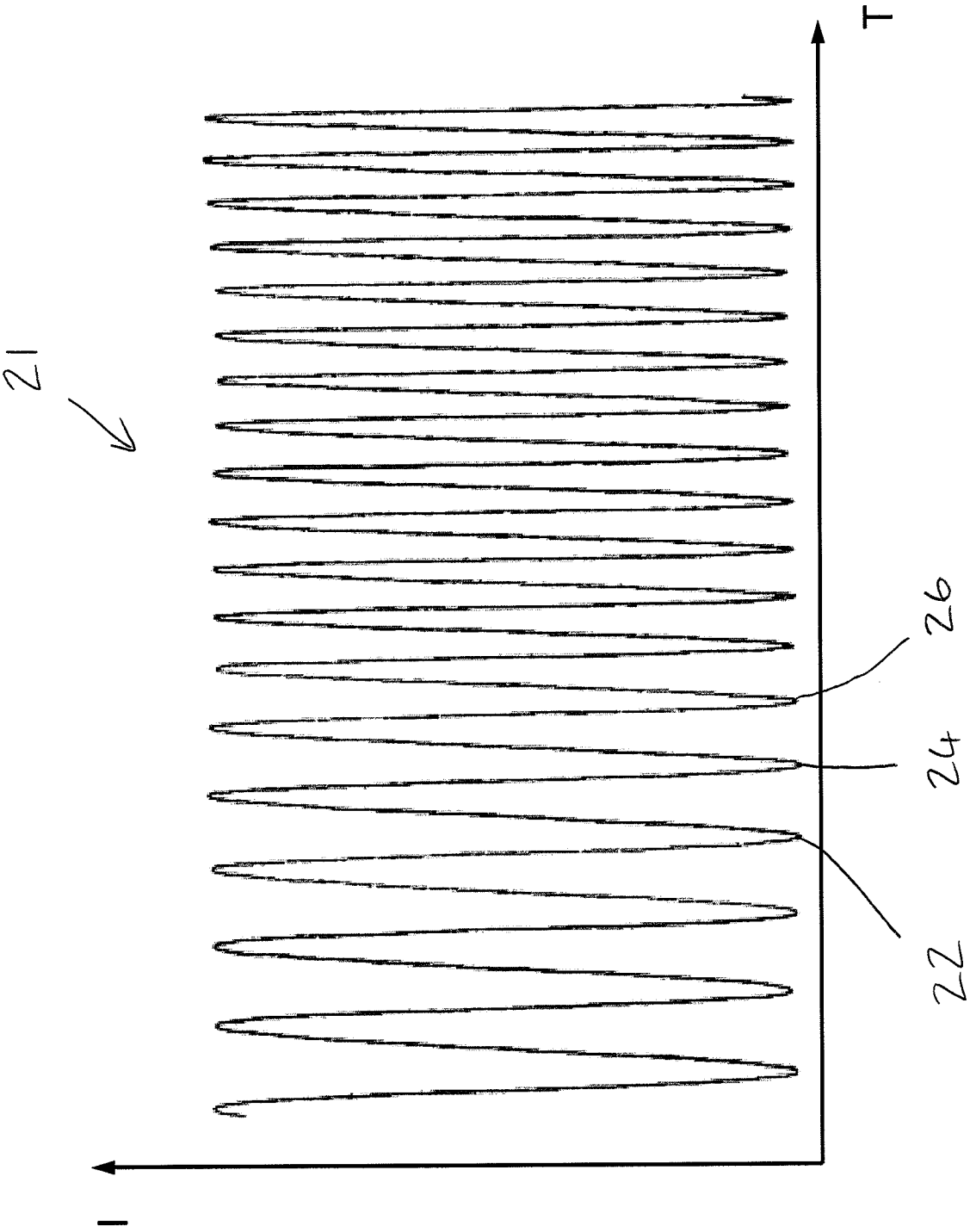


FIG. 2

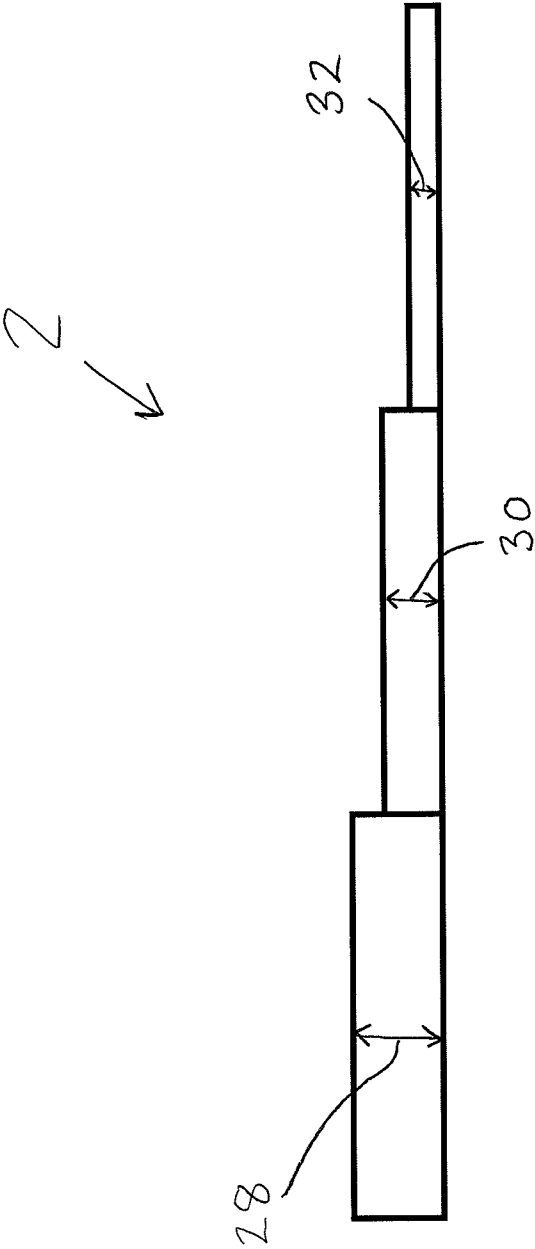


FIG. 3

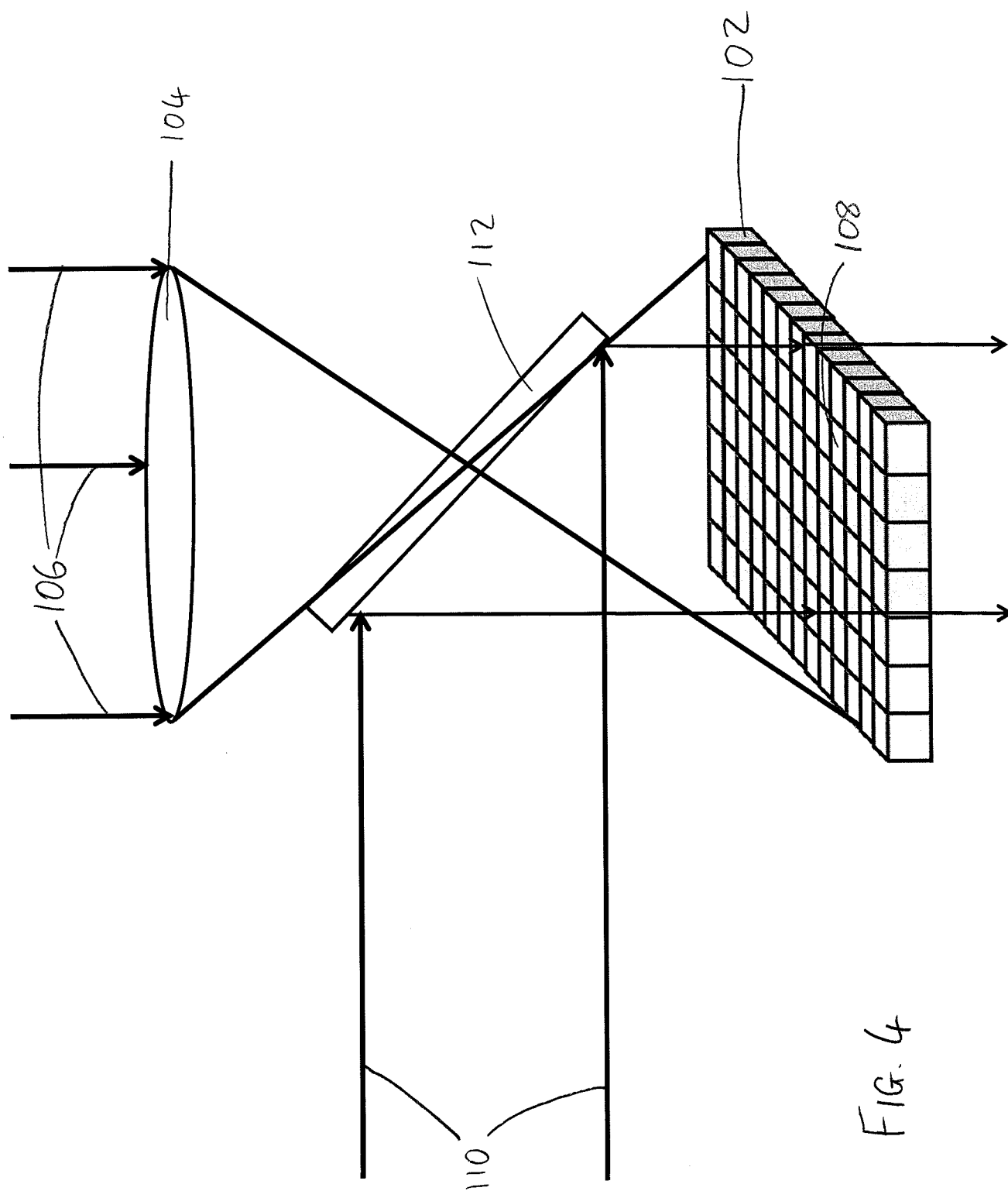


FIG. 4

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2011/051111

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01K11/12
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01N G01K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC, COMPENDEX

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	GB 1 246 432 A (MULLARD LTD [GB]) 15 September 1971 (1971-09-15) the whole document	1-19, 23-42
T	----- BALLMAN A A ET AL: "The growth and properties of strontium barium metaniobate, Sr _{1-x} BaxNb ₂ O ₆ , a tungsten bronze ferroelectric", JOURNAL OF CRYSTAL GROWTH NETHERLANDS, vol. 1, no. 5, December 1967 (1967-12), pages 311-314, XP0000002658469, abstract ----- -/--	



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document but published on or after the international filing date
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
"&" document member of the same patent family

Date of the actual completion of the international search

8 September 2011

Date of mailing of the international search report

30/09/2011

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INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2011/051111

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	BAGDASAROV KH S ET AL: "Interference coloring in lithium tantalate", SOVIET PHYSICS - CRYSTALLOGRAPHY USA, vol. 33, no. 6, November 1988 (1988-11), pages 851-852, XP009151887, ISSN: 0038-5638 the whole document	1-13, 15-36, 38-45
X	----- BÄUMER CH ET AL: "Determination of the composition of lithium tantalate crystals by zero-birefringence measurements", APPLIED PHYSICS LETTERS, AIP, AMERICAN INSTITUTE OF PHYSICS, MELVILLE, NY, US, vol. 82, no. 14, 7 April 2003 (2003-04-07), pages 2248-2250, XP012033696, ISSN: 0003-6951, DOI: 10.1063/1.1566100 the whole document	1,4-13, 15,16, 23,24, 26-36, 38,39
A	----- US 2007/133004 A1 (DUPLAIN GAETAN [CA] ET AL) 14 June 2007 (2007-06-14) abstract; figure 1 -----	14,37

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2011/051111

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
GB 1246432	A	15-09-1971	NONE

US 2007133004	A1	14-06-2007	NONE
